PhilEx Profiling Measurements of Internal Waves and Mixing Processes Final Report

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LONG-TERM GOALS

This project aims to increase our understanding of internal wave processes in straits and archipelagos, including generation of internal waves by wind and tidal forcing, propagation and topographic modification, and cascade to smaller scales through non-linear interactions and breaking. These processes influence low-frequency flows through mixing and momentum transport, and their accurate representation in numerical models is necessary to simulate circulation and property distributions in complex regions. An additional goal is the specific characterization of the circulation and small-scale processes in the Philippines, an under-studied region with potential importance to the South China Sea circulation and the Pacific–Indian Ocean Throughflow.

OBJECTIVES

- To obtain high-resolution measurements of temperature, salinity, and velocity finestructure in the little-studied straits and basins of the Philippine Archipelago (Figure 1) for the purposes of characterizing the spatial and temporal variability of internal tides and near-inertial internal waves, as well as other flow-driven mixing processes.
- To demonstrate and test spectral techniques for the characterization of high-resolution internal wave measurements, including frequency–wavenumber spectra, band-pass filtering, and bi-coherence.
- To provide in-situ data for testing of numerical models of tides and circulation through the archipelago.
- To demonstrate the capabilities of profiling floats for remote surveying of constricted regions over long periods of time with limited ship access.

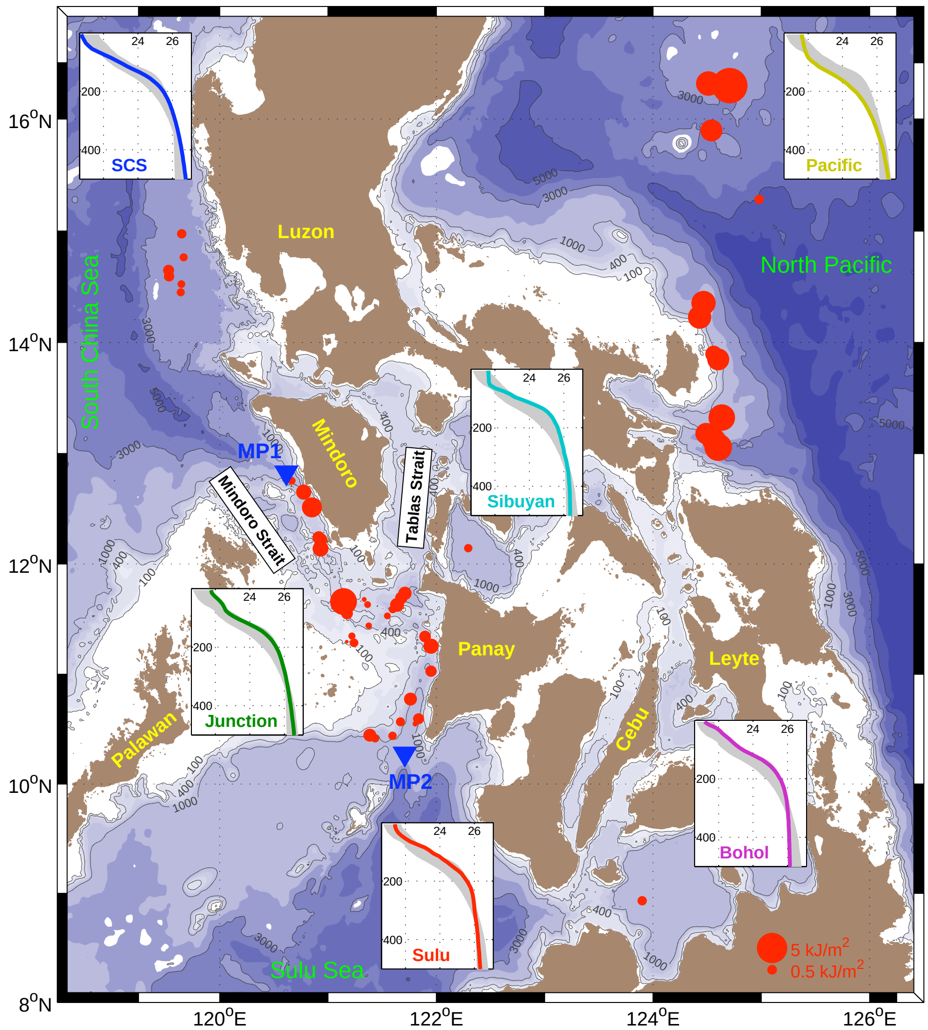

Figure 1: Locations of profiling moorings MP1 and MP2 (blue triangles) and EM-APEX measurements (red dots, sizes proportional to the depth-integrated available potential energy in the internal tide from harmonic fits over 24-hr windows) in the Philippine Archipelago. Inset panels show the density profile in each of the different sub-regions, highlighting the reduced stratification below sill depths in the interior seas. Bathymetric contours are in meters from the STRM30 database.

- To test the ability of EM-APEX floats to perform in a region of low vertical magnetic field strength (the magnetic equator).
- To understand the climatology of internal waves in the diurnal, semidiurnal, and inertial bands (Figure 2), including forcing mechanisms, topographic effects, and dependence on mean flow and stratification.
- To evaluate the importance of the different types of internal waves in the Philippines for mixing and momentum transport.
- To use this information to guide improvements in sub-gridscale parameterizations, leading to improved predictions of oceanic properties and air-sea fluxes.

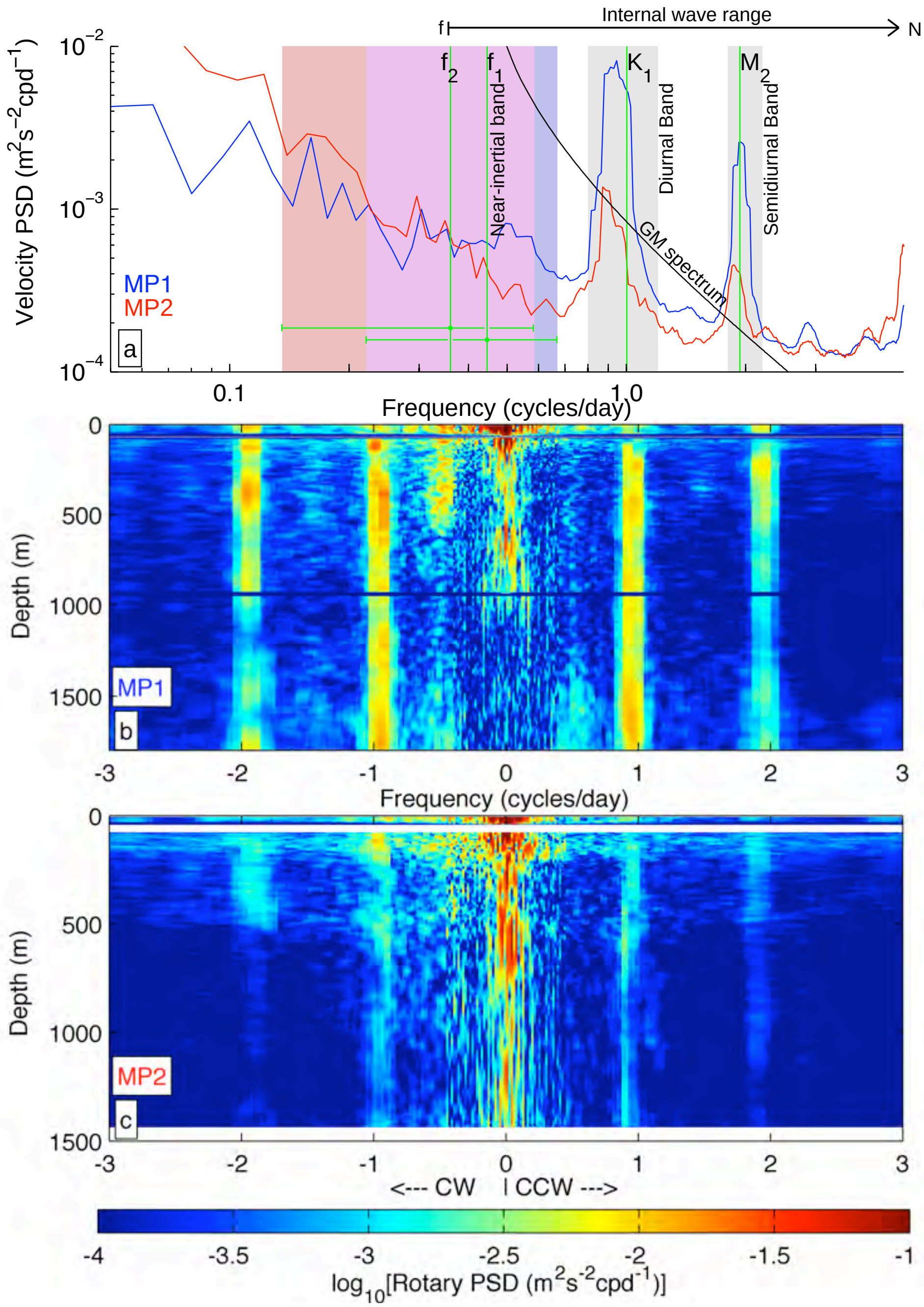

Figure 2: Average (a) and depth-dependent (b and c) rotary frequency spectra of velocity from MP1 and MP2. Tides are stronger at MP1 while low-frequency variability is greater at MP2. Note the clockwise-polarized near-inertial motions in the upper water column at MP1 but linearly-polarized motions near the bottom.

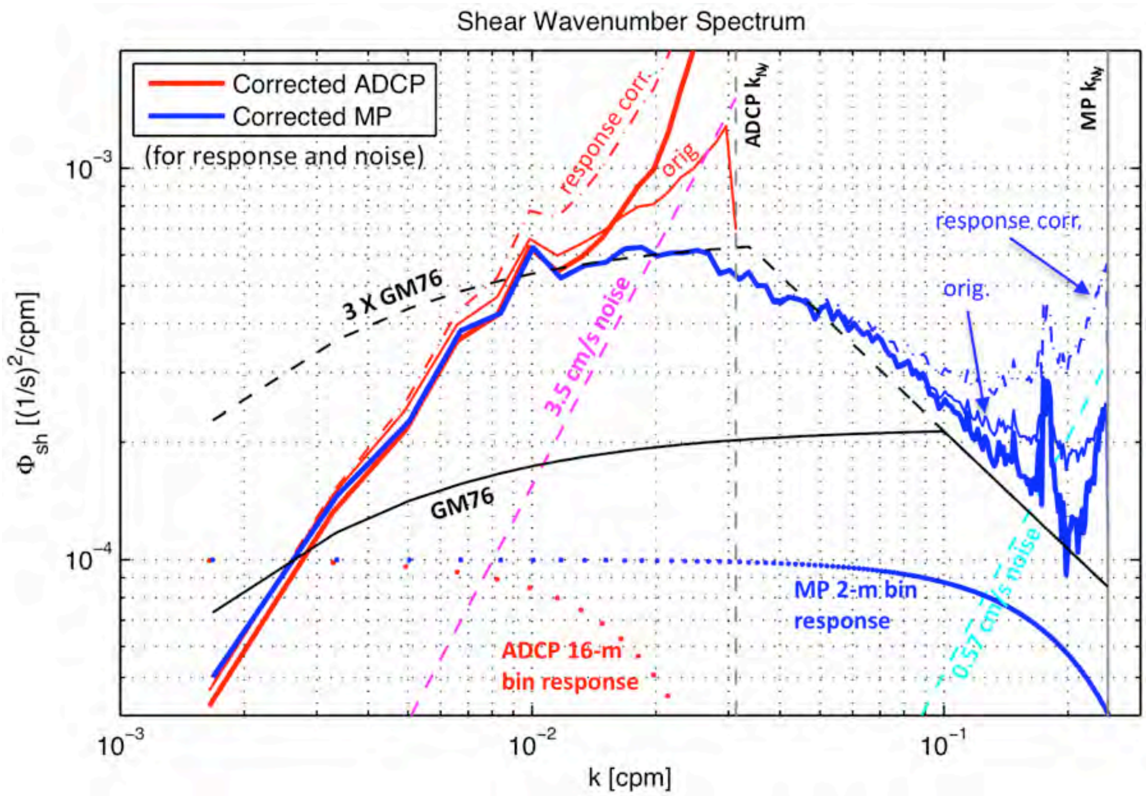

Figure 3: Mid-depth shear wavenumber spectra from overlapping MMP and ADCP instruments on mooring MP1, together with the wavenumber shape of the instrument responses (dotted lines) and noise floor (dashed lines). For greater than 100 m wavelengths the two spectra agree, while for shorter scales the ADCP (red curve) is contaminated by instrument response and noise. The MMP (blue curve) appears to resolve the high wavenumber roll-off of the" saturated" internal wave range to scales of 10 m or less.

APPROACH

This work is a part of a multi-investigator Departmental Research Initiative (DRI) on the "Dynamics of Archipelago Sea Straits." After choosing the Philippines Archipelago as the location for the field experiment (Figure 1), the DRI was given the title "PhilEx." The two components of PhilEx in this component of the experiment were (1) a set of EM-APEX profiling float velocity and CTD measurements distributed throughout the archipelago and spanning the multiple research cruises, and (2) two profiling moorings at the north and south ends of the Mindoro–Panay strait complex.

The EM-APEX floats are a variant on the standard Argo-type profiling float with an electromagnetic velocity sensor that relies on the horizontal motion of the instrument through the vertical component of the geomagnetic field. During most of the PhilEx work, these floats made continuous round-trip profiles between the surface and 500m depth every 3 hours. A principal justification for this was to resolve the semidiurnal tide, which is significant in parts of the archipelago. One disadvantage of the velocity measurement is that the signal-to-noise ratio drops as it approaches the magnetic equator, which runs through Mindanao, the southern island of the Philippines. Though most of the

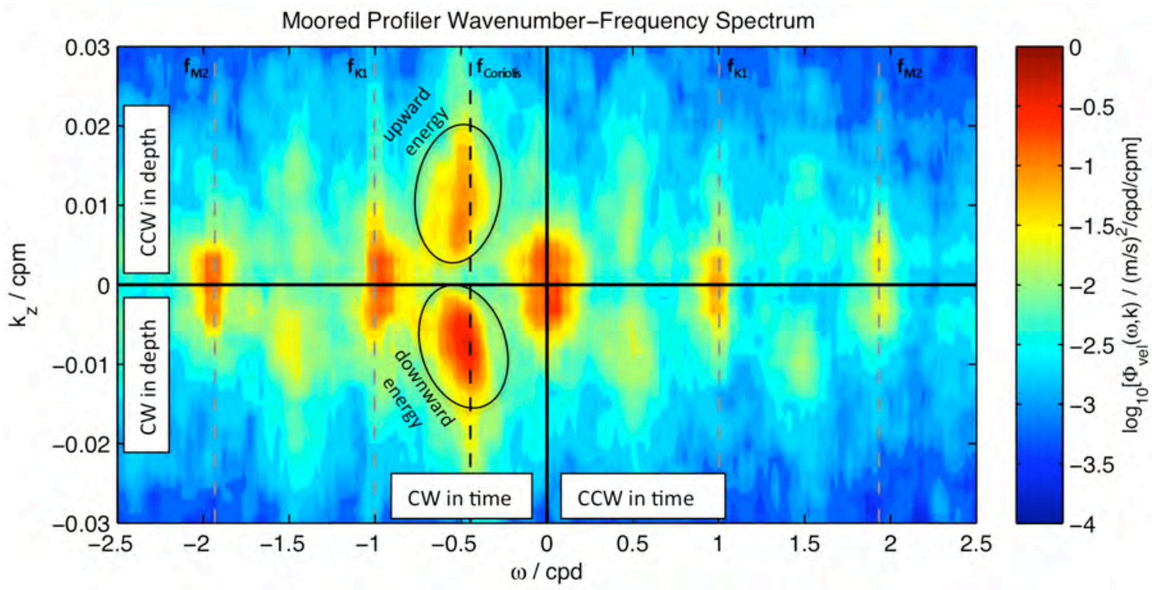

Figure 4: Wavenumber–frequency spectrum from MP1 over the mid-water-column range where strong clockwise near-inertial motions are present. Both upward and downward propagation are apparent (see Figs. 5–7).

measurements were made at least 3° north of the magnetic equator, and none closer than 1°, the low signal is clearly an issue. In addition, the low signal increases the vulnerability to external sources of electric currents, which can appear as spurious velocity signals in the water. In a number of EM-APEX profiles, an ionospheric current known as the "equatorial electrojet" appears to be influencing the near-surface velocity measurements during the day, making the true oceanic tidal signals difficult to estimate. CTD measurements were unaffected by this contamination, however, and analysis of internal tides has been possible using these alone.

The moorings were deployed for a period of just over 2 months and included wire-crawling McLane Moored Profilers (MMP) and acoustic Doppler current profilers (ADCP) to extend the range and to increase the temporal resolution of the mid water column MMP measurements. Performance characteristics of the two shear measurements are shown in Figure 3. One mooring (MP1) was placed in 1800m of water on the

South China Sea end of Mindoro Strait (i.e., northwest of the northern sill). This mooring included 2 MMPs, upward and downward-looking 300 KHz ADCPs at 100m and 1750m depth, and downward-looking 75 KHz ADCP at 100m. The other mooring (MP2), placed in 1500m of water on the Sulu Sea end of Panay Strait (i.e., south of the southern sill), held one MMP and two ADCPs (upward-looking 300 KHz and downward-looking 75 KHz at 100m). Together these positions were chosen to characterize both the generation and radiation of internal waves within the combined strait and the internal wave climate and external influence of the adjacent basins.

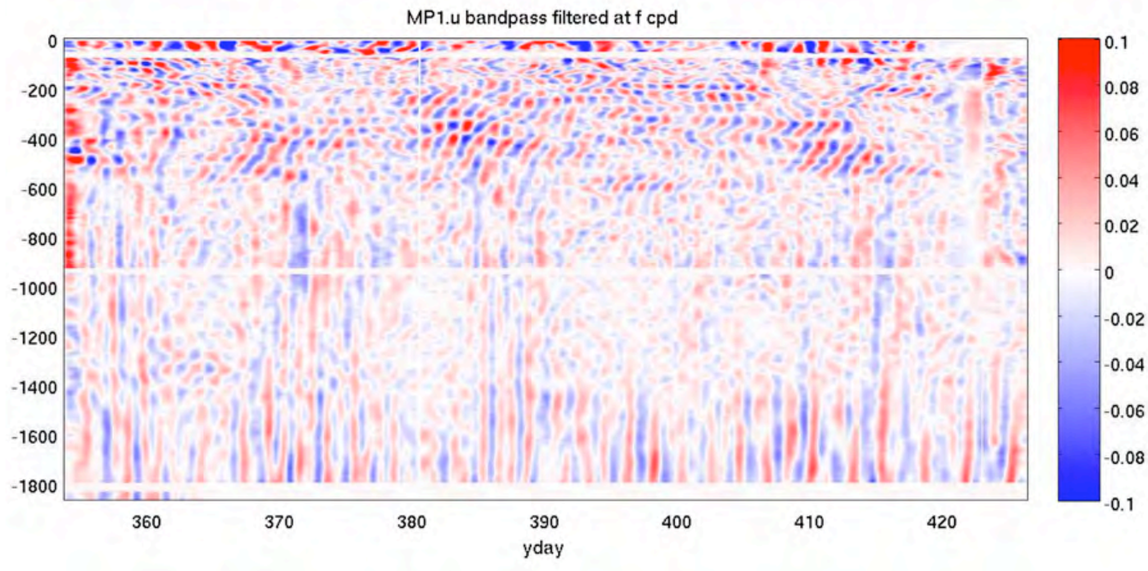

Figure 5: Near-inertial band-passed velocity from MP1. Downward-propagating (upward phase tilt with time) wave packets are present as deep as 600m, with some evidence of upward-propagation shown by the "checkerboard" patterns at certain depths and times. Between 1400m and 1800m (close to the bottom) near-inertial energy is also elevated, but shows little sign of phase propagation at these depths.

WORK COMPLETED

The mooring deployment ended in March 2008 and the EM-APEX floats in mid-2009, with the remainder of the effort focused on quality control, post-processing, and data analysis and interpretation.

Quality control issues included accounting for a conductivity sensor failure on one of the MMPs by using a T–S relation derived from the "good" portion of the record, and adjusting velocity sensor calibrations when an amplitude offset between the two MMPs on mooring MP1 became apparent.

Analysis of the mooring records included the construction of band-passed current records in 3 frequency bands: 0.4, 1, and 2 cycles per day, representing the inertial frequency and diurnal and semidiurnal tides (Figures 2 and 5). Additional steps included the computation of kinetic energy vs. depth (Figure 8), separation of the band-passed signals into clockwise and counter-clockwise rotating components (in both depth and time; Figures 6 and 7), and tidal harmonic analysis. Further analysis, inspired by the suggestion of mid-water column Parametric Subharmonic Instability, included the construction of wavenumber-frequency spectra (Figure 4) and bispectra to characterize the strength of wave-wave interactions between the tidal and inertial bands.

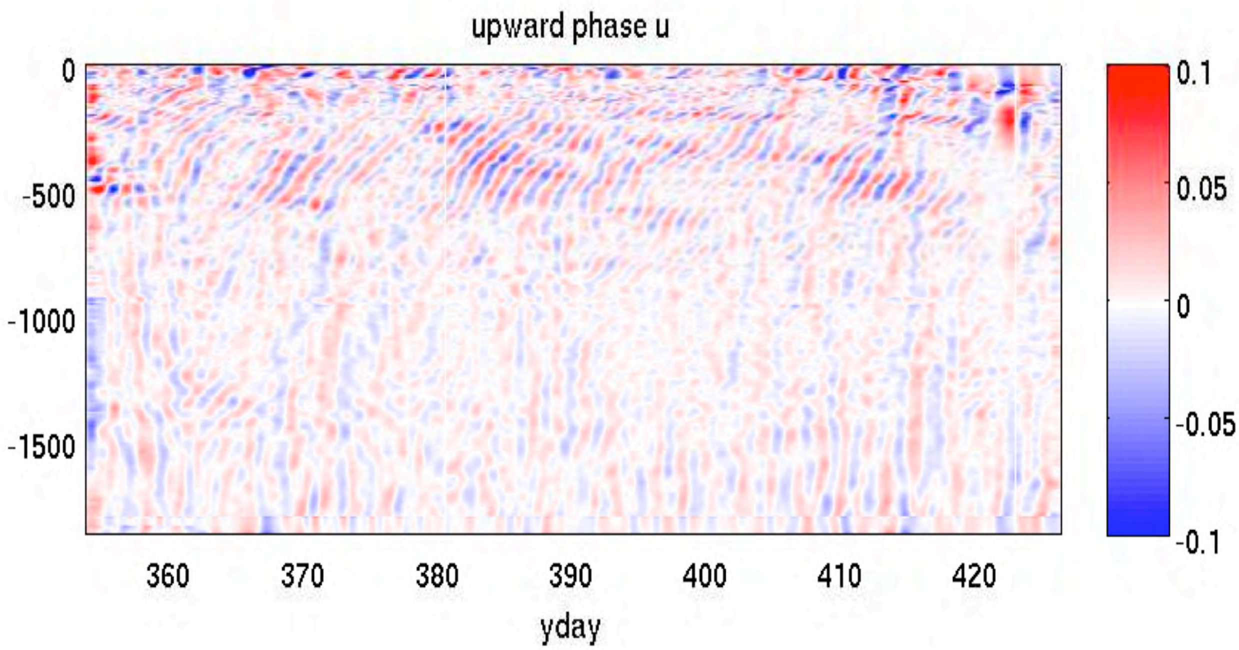

Figure 6: A reconstruction of the clockwise-rotating portion of the rotary spectra with depth. The downward propagating packets in the upper ocean show up more clearly without the checkerboarding. The deep near-inertial energy is only weakly present.

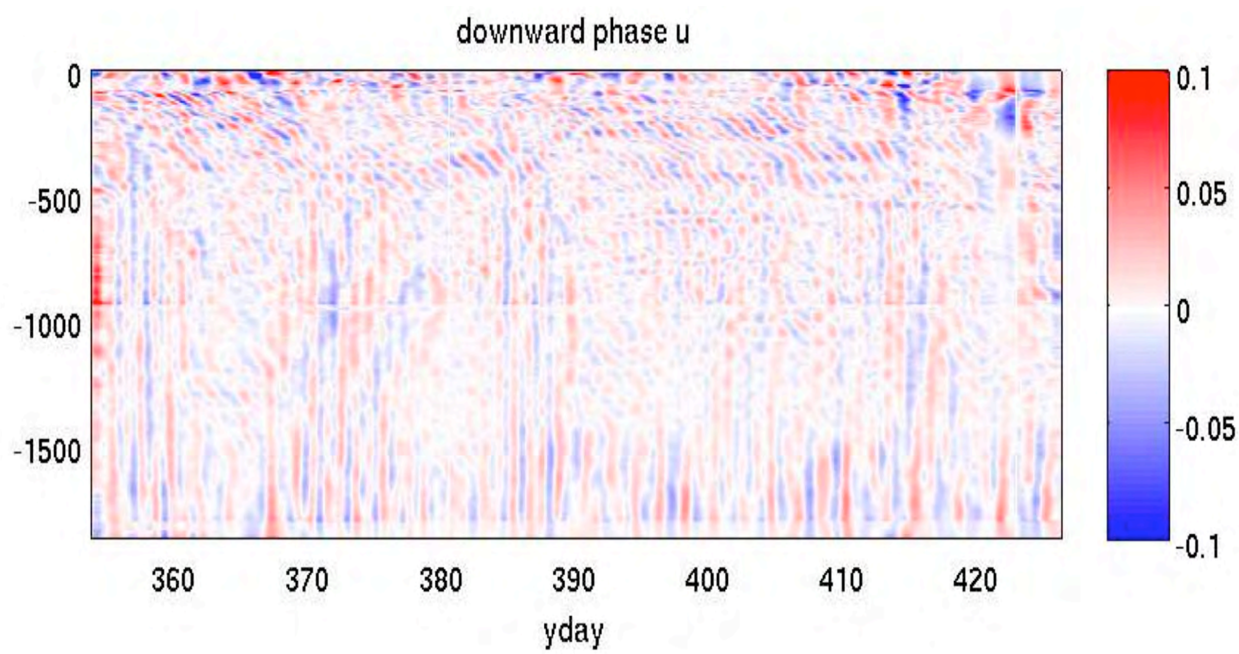

Figure 7: Counter-clockwise rotating portion of the spectra. Upward-propagating waves are present in places, as is the deep near-inertial energy.

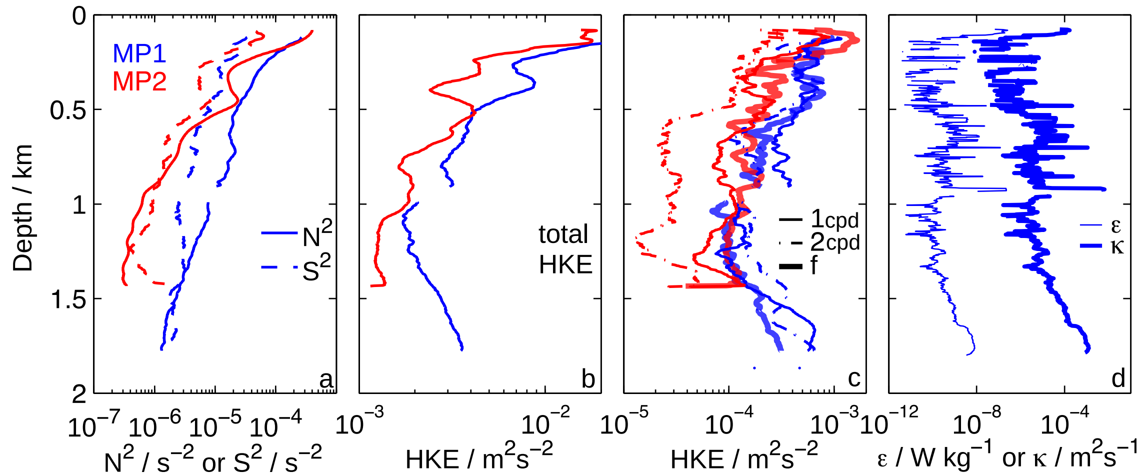

Figure 8: Mean profiles at the two sites of: (a) shear and stratification, (b) total kinetic energy, (c) band-passed kinetic energy in 3 frequency bands (diurnal tide, semidiurnal tide, and near-inertial), and (d) dissipation and diffusivity inferred from density overturns at MP1.

RESULTS

The principal findings to date include the following:

- Diurnal and semidiurnal internal tide signals are evident in the EM-APEX isopycnal displacements, and the geographical distribution of tidal available potential energy illustrates the contrasts among the Philippine basins as well as the transition from the South China to Sulu Seas (Figure 1). Velocity measurements, however, are frequently contaminated by spurious near-surface daytime electric currents—likely related to ionospheric processes.
- Sub-surface shear levels measured by the EM-APEX near the O1 tide critical latitude are somewhat elevated relative to other latitudes, but not to the extent observed by Alford (2008).
- Barotropic tides estimated from the MP1 and MP2 moorings compare well to predictions from the TPXO 7.2 model.
- Tidal energy levels on the South China Sea side of Mindoro Strait (MP1) are significantly larger than on the Sulu Sea side (MP2), while low-frequency (mesoscale) variability is larger at MP2 (Figures 4 and 8).
- Much of the near-inertial variance is in the form of downward-propagating wave packets (Figure 6), though a fair amount of upward-propagating energy is also present (Figure 7).
- Bottom-intensified near-inertial energy at MP1 shows little vertical phase propagation (though is mainly in the counter-clockwise portion of the rotary spectra) and appears to be the result of a canyon-trapped mode (Figures 5 and 7).
- All 3 bands show significant low-frequency modulation. This is clearly a fortnightly spring–neap cycle in the internal tide bands, but with substantial phase shift between the diurnal and semidiurnal cycles.

- Spring-neap modulation of the near-inertial band bears little resemblance to wind forcing, and appears to be related to breakdown of the diurnal tide through parametric subharmonic instability (PSI).
- Mid-depth shear spectral levels at MP1 are elevated above the canonical Garrett–Munk spectrum by about a factor of 3 (Figure 3), while mixing inferred from density overturns suggests weak diffusivity comparable to open ocean background values in the same depth range (Figure 8d). These facts are consistent with the latitude dependence of internal wave mixing shown by Gregg et al (Science 2003).

IMPACT/APPLICATIONS

This work represents the first measurements of the internal wave field in the Philippines and so has considerably improved our understanding of processes occurring there, including interactions with topography and implications for mixing of tracers and momentum. Both the wavefield and the topographic interactions are not well-represented in numerical models, resulting in a considerable need for in-situ data as well as new parameterizations. So far, the measurements have been used to assimilate and compare with regional numerical models (Arango et al and Pullen et al, *Oceanography* 2011) and in further research will permit validation of existing or newly-developed mixing parameterizations.

We have now published two papers from this research (Alford 2008; Girton et al, 2011), and a third (Chinn et al, 2011) is close to submission. Graduate student Brian Chinn will defend his Master's Degree on this work on March 9, 2011.

RELATED PROJECTS

This work is part of the ONR "Dynamics of Archipelago Straits" Departmental Research Initiative (subsequently labeled the Philippines Experiment, or PhilEx) and has been carried out in close collaboration with the other investigators in that project. Scientific discussions among the full group of PIs have been very helpful in defining the physical processes, scientific questions, and geographic locations for study.

Future synergy is expected with Brian Chinn's planned Ph.D. project to explore variations in wavenumber–frequency spectra in a variety of moored datasets, as well as with proposed work by the PIs on the South China Sea circulation. The Mindoro Strait is the deepest connection between the South China Sea and the open ocean after the Luzon Strait, and so has been suggested to carry a significant amount of the mass flux that enters through the deeper strait and upwells due to mixing. The PhilEx measurements to date have not born out this transport prediction, but the enhanced near-bottom mixing observed in our dataset suggest similar internal tide processes occurring throughout the South China Sea.

PUBLICATIONS

Alford, M.H., 2008: Observations of parametric subharmonic instability of the diurnal internal tide in the South China Sea. *Geophys. Res. Lett.*, **35**, L15602, doi:10.1029/2008GL034720.

Chinn, B. S., J. B. Girton, and M. H. Alford. Observations of internal waves and PSI in the Philippines Archipelago. manuscript in prep, 2011.

Girton, J. B., B. S. Chinn, and M. H. Alford. Internal wave climates of the Philippine seas. Oceanography, 24(1):100–111, March 2011.

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